Geothermal / Solar Hybrid Designs: Use of Geothermal Energy for CSP Feedwater Heating

Craig Turchi[1], Guangdong Zhu[1], Michael Wagner[1], Tom Williams[1], and Daniel Wendt[2]

[1]National Renewable Energy Laboratory, Golden, Colorado, USA
[2]Idaho National Laboratory, Idaho Falls ID, USA

Keywords

Geothermal, solar, CSP, hybrid, feedwater heating

ABSTRACT

This paper examines a hybrid geothermal / solar-thermal plant design that uses geothermal energy to provide feedwater heating in a conventional steam-Rankine power cycle deployed by a concentrating solar power (CSP) plant. The geothermal energy represents approximately 11% of the annual thermal input to the hybrid plant. The geothermal energy allows power output from the hybrid plant to increase by about 8% relative to a stand-alone CSP plant with the same solar-thermal input. Geothermal energy is converted to electricity at an efficiency of 1.7 to 2.5 times greater than would occur in a stand-alone, binary-cycle geothermal plant using the same geothermal resource.

While the design exhibits a clear advantage during hybrid plant operation, the annual advantage of the hybrid versus two stand-alone power plants depends on the annual operating hours of the different plants. Annual net power from the hybrid plant matches the combined output from a stand-alone CSP plant and stand-alone geothermal plant when the assumed stand-alone geothermal plant availability is 74% or less. The cost implications are not covered in this study, but the hybrid plant avoids the need for an ORC power block and produces more power during hot afternoons that generally correspond to peak demand periods.

Introduction

Solar thermal power, also known as concentrating solar power (CSP) differs from solar photovoltaic power in that thermal energy is collected and converted into electricity via a thermo-electric power cycle. Thus, CSP shares similarities with other thermo-electric generation methods that use nuclear, fossil, or geothermal heat sources. This commonality has led to frequent and various investigations of ways to combine CSP with other thermal sources. While a multitude of possible integrations are possible, the challenge is to combine two heat sources in a synergistic fashion, that is, one in which benefits are realized by both technologies.

This paper describes a geothermal / solar thermal hybrid design that utilizes low-temperature geothermal heat to provide feedwater heating in a CSP plant that operates at a much higher temperature. The CSP plant drives an air-cooled, steam-Rankine power cycle with superheated-steam inlet conditions of 371°C and 91 bar, and a gross thermal-to-electric conversion efficiency of approximately 35% [1]. This hybrid design allows for integration of the two heat sources at temperatures that best align with their resources and collection technologies.

Background

In 2013 Zhou et al. summarized a number of studies that proposed or examined geothermal / solar thermal hybrids [2]. The reports listed in Zhou's paper included various schemes for use of

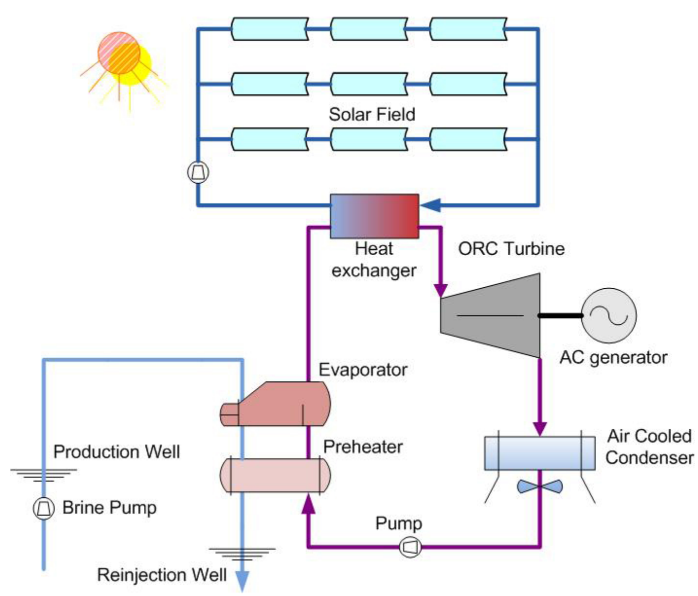

Figure 1. Hybrid geothermal / solar thermal system with solar heating of the ORC working fluid [2].

the solar energy, including (i) preheating binary cycle brine, (ii) preheating flash cycle brine to increase vapor fraction in the flash tank, (iii) superheating the organic Rankine cycle (ORC) working fluid, and (iv) reheating brine or condensate and recycling the fluid to the power cycle.

Zhou assumed an ORC binary-cycle plant and studied a design that provided solar heat into the power cycle working fluid (Figure 1). An important feature of Zhou's work is the conclusion that either of two control strategies designed to maintain the working fluid near its saturation point (i) fixing mass flow and varying temperature and pressure, or (ii) fixing temperature and pressure and varying mass flow rate, resulted in comparable thermodynamic performance. These control strategies were nearly as effective as assuming the system was optimized by allowing mass flow, temperature, and pressure to simultaneously vary, which was assumed to be too complex for plant control. Zhou also proposed a more complex integration that included a dedicated turbine for the solar-heated working fluid combined with a low-temperature turbine that can operate on geothermal energy alone.

Greenhut et al. [5] compared different hybrid configurations assuming the use of a low-temperature geothermal resource (150°C). The low thermal efficiency of a binary cycle running at ca. 150°C was a significant limitation to hybrid plant efficiency. For this reason, the authors proposed using solar energy to heat and flash the brine to produce 200°C, 15.5 bar steam. These conditions allowed operation of a steam turbine at ca. 200°C and use of the flash tank liquids to boost the organic working fluid to 180°C. When solar energy was not available the plant operated the ORC cycle alone at the lower brine temperature. Such a design was able to increase thermal efficiency from approx. 11% with the low-temp ORC power block to about 17.5% with the combined steam / ORC power system. However, moving to a flash-plant design with steam and ORC turbines brings additional complexity as well as scaling and emission concerns.

A general challenge for any hybrid design is how to efficiently accommodate two different operating points, typically corresponding to operation with and without solar energy input. Binary geothermal power plants generally have low operating temperatures (~150°C) and correspondingly low thermal-to-electric efficiency. In contrast, modern solar thermal collectors can readily achieve temperatures of 390°C, but are available on an intermittent basis. Designing a single power block to handle these different conditions is challenging, yet using two different power units increases cost and complexity, and negates advantages of having an integrated system. Of course, solar energy can be collected at lower temperature or down-graded for use in a lower temperature ORC power cycle. There are some advantages to using low-temperature solar collectors, for example, heat losses will be lower and lesser optical and material requirements can lower the cost of the solar collectors. Yet the experience of the CSP industry indicates that high-temperature and high-efficiency systems are required for favorable economics.

In 1979, the Aerospace Corporation completed a study of geothermal / solar thermal hybrids for the U.S. Department of Energy [3]. The report concluded that two issues challenge the economics of hybrid designs. The first issue is the low conversion efficiency of typical binary-cycle geothermal power cycles. This makes their use for conversion of (relatively expensive) solar-thermal energy into electricity unappealing. Flash-cycle plants offer higher efficiency, but suffer emission issues from non-condensable gases. The potentially attractive ability to heat the brine directly in solar collectors prior to flashing is countered by fouling issues. The report concluded that the best integration was to use the geothermal fluid to provide the low-temperature feedwater heating needs for a higher-temperature, higher-efficiency steam-Rankine power cycle that is driven by a CSP system.

Approach

This study simulates the use of a geothermal resource to provide feedwater heating in a CSP system running a superheated-steam-Rankine power cycle. The steam power cycle was modeled in IPSEpro process simulation software (enginomix.net), where IPSEpro was used to examine the thermodynamic performance of the power cycle with and without geothermal energy integration. IPSEpro calculated the performance of the cycle at its normal design point and at off-design conditions representing partload operation and varying ambient temperature. These results were used to map performance as a function of ambient and operating conditions that was then used in the calculation of annual system performance.

A representative steam-Rankine power cycle for a parabolic trough CSP plant was created in IPSEpro and is shown schematically in Figure 2. This power cycle has five feedwater heaters (FWH), an HTF-to-steam boiler and superheater train, and single-stage reheat. Our modeling assumes that all scenarios – solar,

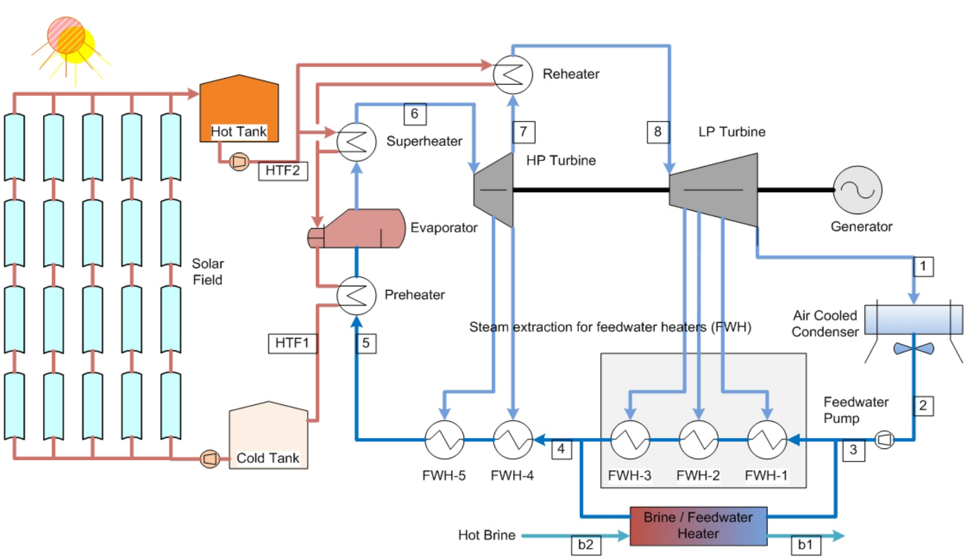

Figure 2. Schematic of a representative CSP plant showing energy from geothermal brine replacing the three low-temperature feedwater heaters (FWH-1, FWH-2, and FWH-3), thereby eliminating steam extractions from the low-pressure turbine. Open, hot (direct contact) FWHs are shown for simplicity, although the model uses closed FWHs.

geothermal, and hybrid – use air-cooled condensers to minimize water consumption. In the stand-alone solar plant, condensate from the air-cooled condenser runs through a series of FWHs that preheat the water with steam extracted from various stages of the power turbine. The first three FWHs raise the feedwater from the condenser outlet temperature (which depends on ambient conditions) to approximately 140°C. The hybrid-plant scenario looks at the effect of replacing those steam extractions with a brine-to-feedwater heat exchanger operating over the same temperature conditions (see Figure 2).

The solar resource was estimated using the typical meteorological year (TMY) weatherfile for Imperial, CA. The region around Imperial possesses good solar thermal and geothermal resources, e.g., Salton Sea and Cerro Prieto geothermal sites. TMY data sets are hourly values of solar radiation and meteorological elements for a 1-year period [4]. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations. The TMY file covering 1998-2009 for Imperial, CA was downloaded from the National Renewable Energy Laboratory's (NREL) Solar Power Prospector at http://maps.nrel.gov/prospector.

The annual performance of the stand-alone solar and hybrid systems was modelled using the System Advisor Model (SAM, https://sam.nrel.gov/). SAM is a free performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. First, SAM's Physical Trough model was used to simulate the hourly performance of a conventional, utility-scale parabolic trough plant. The default values present in SAM-2014-01-14 for performance and financial inputs were used, with the exception of the location as described above and assumption of dry cooling. Following the SAM default case, the CSP and hybrid plants were assumed to include 6 hours of thermal energy storage. Second, the power block routine within the SAM Physical Trough model was modified to incorporate geothermal energy integration as modeled by IPSEpro. Results from the two scenarios provided a comparison of the annual performance of the hybrid plant and the conventional CSP parabolic trough plant.

The stand-alone CSP cycle efficiency provided in Table 1 was estimated by WorleyParsons Group and is documented in reference [1]. This value is higher than that estimated by our IPSEpro model (approx. 31.9%). The IPSEpro model is used to explore the relative behavior of the hybrid cycle. For absolute cycle efficiency we rely on the more detailed WorleyParsons optimization. SAM takes as an input the design-point gross power-cycle efficiency as reported in Table 1. SAM estimates gross power and parasitic loads on an hourly basis and calculates the corresponding net power output.

The assumed stand-alone CSP plant produces 100 MWe, net at design-point conditions and the energy from the LP turbine steam extractions totals 43 MW_{th} (see Table 1). The assumed geothermal plant is sized to supply this energy, which corresponds to a brine flow rate of approximately 122 kg/s, assuming a 150°C resource and 70°C re-injection temperature.

Lastly, a model for ORC geothermal plants developed at Idaho National Laboratory (INL) was used to simulate the performance of a stand-alone, binary-cycle geothermal plant at the same site [6]. The stand-alone geothermal plant was assumed to run an isobutane ORC with variable-frequency drive isobutane pumps, variable-geometry turbine nozzle vanes, and an air-cooled condenser. The median annual ambient temperature of Imperial, CA is approximately 25°C; this value was selected as the ambient design-point temperature. Other design parameters including heat exchanger minimum temperature approach values, turbomachinery fluid and mechanical efficiencies, and frictional pressure losses at the design point were set equal to the values specified in Section 3.3 and adjusted for off-design operation as described in Section 4 of Reference [6]. No constraints on the generator output or the geofluid temperature exiting the plant were imposed. The models allowed comparisons between the hybrid design and separate CSP and geothermal plants.

Table 1. Plant characteristics. Input values used the default settings for SAM's CSP Physical Trough model except where noted. Geothermal conditions and efficiencies calculated using [6].

Parameter	Value
Stand-alone CSP plant net capacity	100 MWe
Solar field outlet temperature	391°C
Solar field area (held constant for stand-alone CSP and hybrid cases)	910,000 m^2
Stand-alone CSP design-point, gross thermal efficiency (dry cooled, T_{amb} = 42°C, 16K ITD)	35.4%
Location	Imperial, CA
Geothermal resource temperature	150°C
Brine flow rate (assuming 70°C injection temperature)	128 kg/s
Geothermal capacity	43 MW_{th}
Stand-alone geothermal design-point, net thermal efficiency, $\eta_{g0,design\text{-}point}$ (dry cooled, T_{amb} = 25°C, 15K ITD)	8.5%
Stand-alone geothermal design-point net exergy efficiency (dry cooled, T_{amb} = 25°C, 15K ITD)	28.9%

Results

Hybrid Benefit to Solar Technology

Figure 3 shows IPSEpro's estimated net thermal efficiency of the stand-alone CSP power cycle and the proposed hybrid plant as a function of power block output (recall that design-point output of the stand-alone CSP plant is 100 MWe). The data in Figure 3 are normalized by the design-point efficiency of the stand-alone CSP plant (see Table 1). First-law, thermal-to-electric efficiency is defined by the work produced divided by the thermal energy input (see Nomenclature section for variable definitions):

$$\eta_{s0} = W_{s0} / Q_{s0} \tag{1}$$

$$\eta_{hyb} = \frac{W_{hyb}}{\left(Q_s + Q_g\right)} \tag{2}$$

$$\bar{\eta}_{s0} = \frac{\eta_{s0}}{\eta_{s0,\ design-point}} \tag{3}$$

$$\bar{\eta}_{hyb} = \frac{\eta_{hyb}}{\eta_{s0,\ design-point}} \tag{4}$$

The SAM user defines the design-point case by specifying the ambient temperature, air-cooled condenser initial temperature difference (ITD), rated gross cycle capacity, and gross cycle efficiency. During annual simulations, SAM calculates gross cycle efficiency as a function of ambient temperature and cycle load on an hourly basis by using the performance map and site weather data. SAM also tracks plant parasitic loads such as cooling fans, HTF pumps, and solar collector tracking, and uses these values to calculate hourly net power.

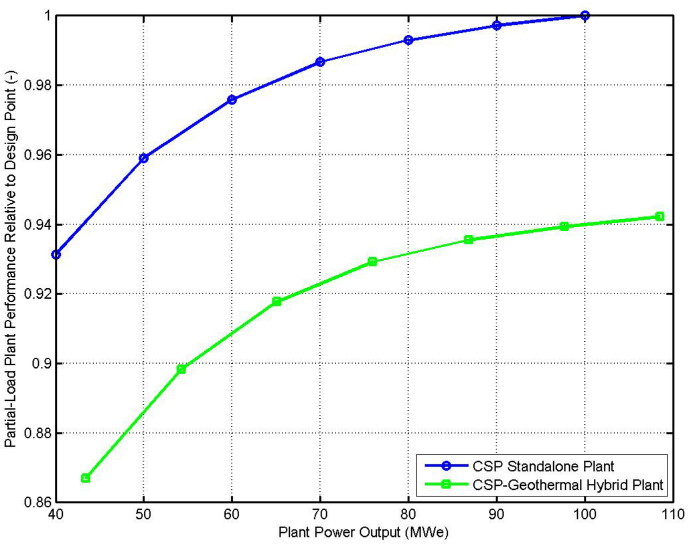

Figure 3. Stand-alone CSP plant ($\overline{\eta}_{s0}$) and hybrid plant net thermal efficiency ($\overline{\eta}_{hyb}$) vs. plant load. The efficiencies are normalized by the design-point, stand-alone CSP efficiency (see Table 1).

Three results are apparent from Figure 3. First, cycle efficiency falls off as the plant drops to lower output (as expected). Second, the hybrid power cycle has a lower overall cycle efficiency than the stand-alone solar case. This drop in efficiency results from the inclusion of low-temperature geothermal energy, which decreases the average temperature of energy addition to the power cycle and, following Carnot's theorem, decreases thermal conversion efficiency.

In contrast to the thermal efficiency, the exergy efficiency of the hybrid plant (Eqn 5) exceeds that of the stand-alone CSP plant (see Figure 4), indicating more effective utilization of the available heat sources.

$$\eta_u = \frac{W_{hyb}}{E_s^{'} + E_g} \tag{5}$$

Where exergy from solar is given by:

$$E_s^{'} = \dot{m}_{HTF} \begin{bmatrix} \left(h_{HTF2} - h_{HTF1}\right) - \\ T_{amb}\left(s_{HTF2} - s_{HTF1}\right) \end{bmatrix} \tag{6}$$

and exergy from geothermal from geothermal is:

$$E_g = \dot{m}_b \begin{bmatrix} \left(h_{b2} - h_{amb}\right) - \\ T_{amb}\left(s_{b2} - s_{amb}\right) \end{bmatrix} \tag{7}$$

The solar exergy definition (Eqn 6) follows the suggestion of Greenhut et al. [5], and defines exergy to account for the fact that

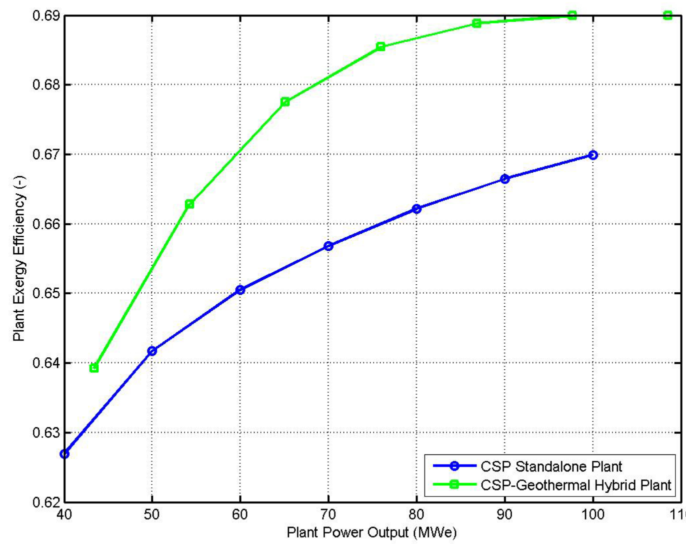

Figure 4. Stand-alone CSP plant and hybrid plant net exergy efficiency as a function of Plant power output.

exergy remaining in the HTF is not lost, but recycled to the solar field. The subscripts correspond to stream labels shown in Figure 2.

The third result from Figure 3 is the greater power output from the hybrid plant. While the hybrid cycle thermal efficiency is lower than the stand-alone CSP case, the overall power output from the hybrid plant is greater, due to inclusion of the geothermal energy. This is indicated in Figure 3 by the shift in the hybrid plant data points (which correspond to the same solar-thermal input) to higher plant power output. For example, the power output at design point has risen from 100 MWe to 108.5 MWe.

If one views the geothermal energy as "free" to the solar plant, this greater power output represents a performance boost of 8.5% (at design point) above that of the stand-alone solar case. From the solar plant perspective, the benefit of the hybrid design is higher exergy efficiency resulting in greater total power output for the same solar-thermal input.

Hybrid Benefit to Geothermal Technology

The benefit of the hybrid design from the geothermal perspective is manifested in a higher thermal and exergy efficiency compared to a stand-alone geothermal plant.

Mathur [3] used the simple ratio of hybrid efficiency to stand-alone geothermal efficiency, η_{hyb} / η_{g0}, to illustrate the benefit of the hybrid design. We prefer to define a geothermal efficiency ratio (*GER*) estimated by comparing the efficiency at which geothermal energy is converted in the hybrid plant, η_g, with stand-alone geothermal efficiency, η_{g0}:

$$GER = \frac{\eta_g}{\eta_{g0}} = \frac{\left(W_{hyb} - Q_s \eta_{s0}\right) / Q_g}{\eta_{g0}} \tag{8}$$

In *GER*, power contribution from solar energy is estimated as the solar thermal energy, Q_s, multiplied by its conversion efficiency in the stand-alone CSP plant, η_{s0}. This product is subtracted from the total hybrid plant power generation, W_{hyb}, to yield a conservative estimate (lower bound) of the power contribution from geothermal energy. The result is conservative, because the energy efficiency of the hybrid plant is actually slightly lower than in the stand-alone solar plant. This definition accounts for the lower thermal efficiency imposed on the solar plant by inclusion of the low-temperature geothermal energy.

Figure 5 and Figure 6 compare geothermal energy conversion efficiency for a stand-alone geothermal plant and the hybrid. The values indicate a *GER* that is 1.7 to 2.5, indicating more efficient use of the geothermal energy in the hybrid than in a stand-alone geothermal plant. Note that this represents conversion of geothermal energy only; the overall hybrid plant efficiency is on the order of 3.6 times greater than η_{g0}.

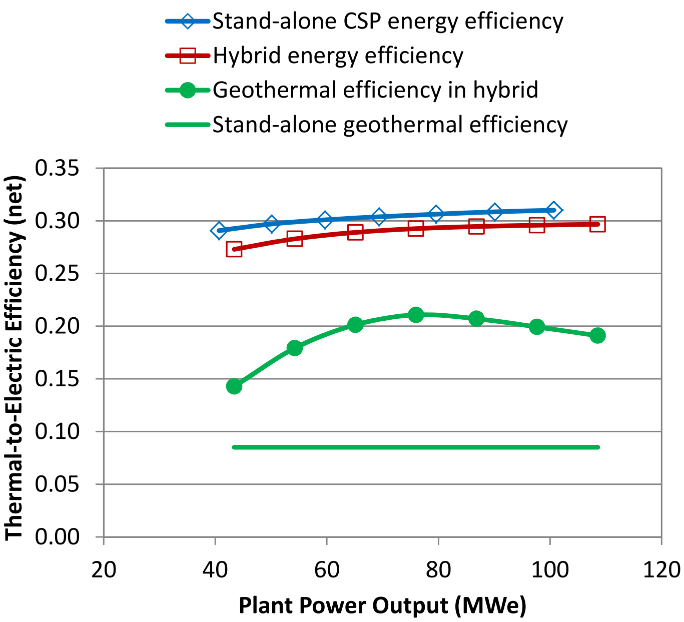

Figure 5. Comparison of system efficiencies: geothermal energy conversion efficiency in the hybrid plant (η_g), exceeds the stand-alone geothermal plant efficiency (η_{g0}) by a factor of 2 or more.

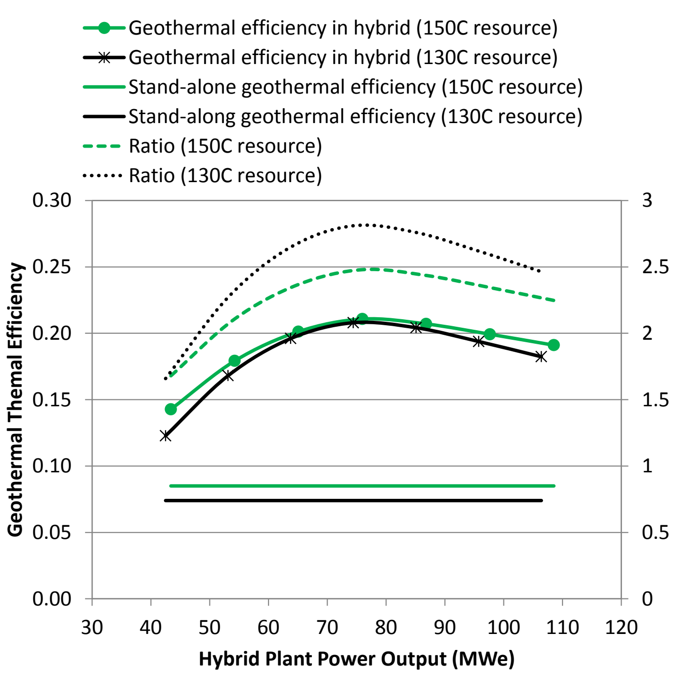

Figure 6. Impact of geothermal resource temperature on the geothermal efficiency in a hybrid plant and in a stand-alone geothermal plant.

An issue that often plagues geothermal power plants is degradation of the resource over time. The geothermal resource temperature or flow rate may fall with time, leading to a serious drop in power output from the geothermal plant. This behavior may trigger drilling of additional production well(s), at significant expense and risk. In the hybrid plant, the impact of decreasing geothermal energy can be offset by instigating or increasing steam extraction from the LP turbine, with a relatively minor penalty to plant output. Figure 6 shows how geothermal efficiency in the hybrid plant, η_g, and in a stand-alone geothermal plant, η_{g0}, change if the resource temperature falls from 150°C to 130°C. As indicated by the efficiency ratios, the relative advantage of the hybrid plant increases when the resource temperature drops.

In summary, the benefit of the hybrid from the geothermal perspective is the higher geothermal energy conversion efficiency obtained in the hybrid plant and less sensitivity to ambient conditions and resource degradation.

Annual Performance

The preceding analysis suggests advantages for the hybrid system relative to both the solar and geothermal stand-alone plants. The next step is to determine how this potential manifests itself over the course of a typical year, where solar conditions and ambient temperature are constantly changing. The comparison is made by modeling a stand-alone CSP plant in SAM, using INL's ORC model for a stand-alone binary-cycle geothermal plant, and finally modeling the proposed hybrid design in SAM with the use of the modified power block algorithm.

The overall comparison between the hybrid vs. two stand-alone plants can be measured by the figure of merit (*FM*) suggested by Zhou [2]:

$$FM = \frac{W_{hyb}}{W_{s0} + W_{g0}} \tag{9}$$

$$FM_{annual} = \frac{W_{hyb,annual}}{W_{s0,annual} + W_{g0,\,annual}} \tag{10}$$

A favored hybrid design is indicated by $FM_{annual} > 1$, which means the hybrid produces more energy than two stand-alone power plants using the same capacity solar and geothermal resources. *FM* can be calculated instantaneously (Eqn 9) or annually (Eqn 10).

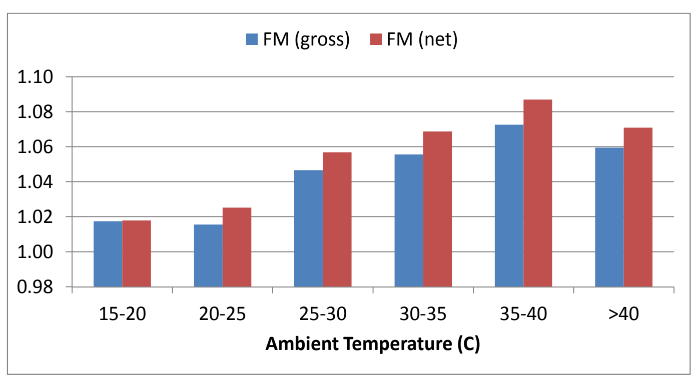

Figure 7. Figure of Merit (Eqn 9) for the hybrid plant when operating. Annual average values are 1.048 for gross generation and 1.059 for net generation.

Figure 7 shows the results for net- and gross-power hourly *FM* during the year when the hybrid plant is operating. The bars depict average hourly *FM* for different ambient temperature ranges. The average *FM* exceeds 1 in all cases, indicating the hybrid plant is producing more power than two, stand-alone CSP and geothermal plants of equivalent thermal capacities to that used in the hybrid. A greater benefit is realized at higher ambient temperatures because the hybrid plant is less affected by ambient temperature than the performance of a stand-alone geothermal plant.

The latter point is also illustrated by plotting the hourly *GER* (see Eqn 8) as a function of ambient temperature. Average *GER* is highest during periods of high ambient temperature, showing that use of the geothermal energy for feedwater heating in the CSP plant is much more effective than use in a stand-alone geothermal plant during these periods, due to the ORC's sensitivity to condenser pressure.

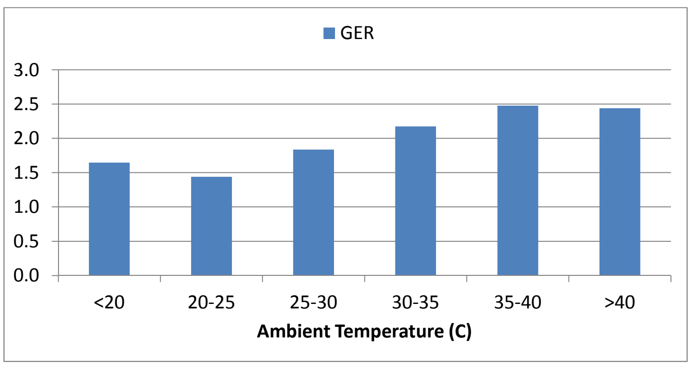

Figure 8. Average Geothermal Efficiency Ratio (*GER*) for different ambient temperatures when the hybrid plant is operating. Values greater than 1 indicate superior geothermal-to-electric conversion efficiency in the hybrid.

An interesting finding from the annual analysis was a small decrease in hybrid plant efficiency at low condenser pressures (i.e., low ambient temperature). The result was counter-intuitive as cycle efficiency normally increases as ambient temperature falls. This behavior was attributed to use of more geothermal energy to preheat the lower-temperature condensate to the target feedwater temperature at point 4 in Figure 2 – a temperature that was assumed to be a fixed value in the model. As previously described, a greater contribution for geothermal energy results in a lower overall cycle efficiency. The results suggest that more sophisticated integration schemes, for example, varying steam extraction rates, could yield additional benefits in cycle performance.

Impact of Annual Operating Hours

The *FM* and *GER* values strongly favor the hybrid design *when the hybrid plant is operating*. However, the solar plant has an annual capacity factor of about 42%, meaning the geothermal energy can heat feedwater for only about 42% of the year. Consequently, the value of FM_{annual} depends on the annual capacity factor of the different plants.

Figure 9 shows how annual *FM* varies with the capacity factor of the stand-alone geothermal plant. The breakeven point ($FM_{annual} = 1$) in this study falls at a capacity factor of about 0.74. If the solar and hybrid plants are designed with more thermal energy storage to achieve capacity factors of 0.56, the FM_{annual} value would never fall below 1 (dotted line). Also shown in Figure 9 are the results if one employs an ORC power block for use when the CSP plant is offline (dashed line). In this scenario, FM_{annual} is never lower than 1.02. The ORC power block is estimated to run with an annual-average net efficiency of 9.2%, which is higher than the value of 8.6% estimated for the stand-alone geothermal. The higher efficiency results from use of the ORC only when the CSP plant is offline, which typically corresponds to cooler ambient conditions. Of course, adding another power block eliminates that cost-saving advantage of the hybrid integration.

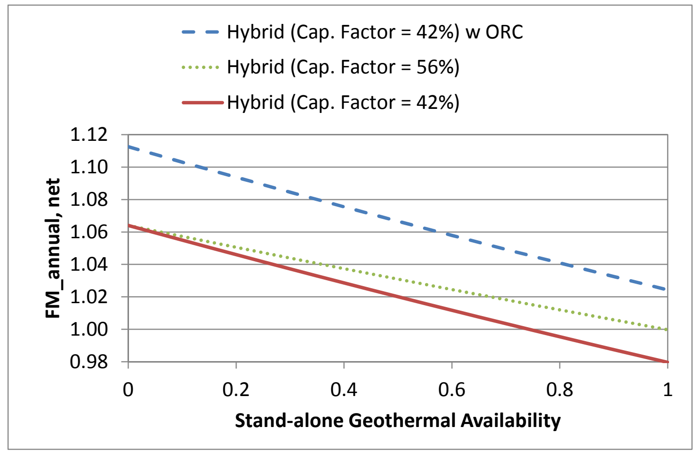

Figure 9. Annual figure of merit, FM_{annual}, for the hybrid design. A value greater than 1 indicates the hybrid produces more energy than the combined output of a stand-alone geothermal and stand-alone CSP plant.

Conclusions

This paper examined a hybrid geothermal / solar-thermal plant design that uses the geothermal energy to provide feedwater heating in a conventional steam-Rankine power cycle such as used by parabolic-trough CSP plants. The geothermal energy represented 11.4% of the annual thermal input to the hybrid plant. The geothermal energy allowed power output from the hybrid plant to increase by about 8.5% relative to a stand-alone CSP plant with the same solar-thermal input. Geothermal energy was converted to electricity at an efficiency of 1.7 to 2.5 times greater than would occur in a stand-alone, binary-cycle geothermal plant at the same site. These benefits led to the hybrid plant generating approximately 6% more power at design-point compared with two stand-alone plants.

While the design exhibited a clear advantage during operation, the annual generation advantage of the hybrid versus two stand-alone power plants depended on the total annual operating hours of the plants. Annual generation from the hybrid design exceeds that of two stand-alone plants only if the stand-alone geothermal plant operates at an annual capacity factor of 74% or less. (Note that in this study the hybrid plant had a capacity factor of 42%.)

The cost and revenue implications of the hybrid design have not been assessed in the present analysis, but are expected to favor the hybrid design due to the elimination of the geothermal power block and the good correlation of solar resource with electricity demand in the US southwest that leads to higher pricing per kWh during plant operation. Revenue and cost advantages will be explored in future work. Other potential benefits for future examination include:

- Utilizing geothermal energy to maintain the steam turbine in a hot-standby mode overnight, thereby improving plant start-up time in the morning and avoiding that energy parasitic on the solar plant,
- Examining the benefits with alternative CSP plant designs, for example, molten-salt power towers running at higher efficiency and greater capacity factor than the trough plant assumed here, and
- Assessing if lowering the brine flow rate overnight will extend geothermal resource life, and
- Testing if addition of an ORC to operate on the available geothermal energy when the CSP plant is offline (e.g., overnight) provides a net cost benefit.

Nomenclature

Acronyms:

CSP = concentrating solar power
GER = geothermal efficiency ratio
HP = high pressure
HTF = heat transfer fluid
INL = Idaho National Laboratory
ITD = initial temperature difference
LP = low pressure
NREL = National Renewable Energy Laboratory
ORC = organic Rankine cycle
SAM = System Advisor Model

Variables:

Q = *thermal energy*
E = *exergy*
W = *work (i.e., electrical energy)*
h = *specific enthalpy*
s = *specific entropy*
$\dot{m}$ = *mass flow rate*
T = *temperature*
η = *thermal (1st law) efficiency*
η_u = *utilization (2nd law) efficiency*

Subscripts:

amb = *evaluated at ambient conditions*
b = *geothermal brine*
g = *geothermal contribution within hybrid*
g0 = *stand-alone geothermal*
hyb = *hybrid*
HTF = *solar heat transfer fluid*
s = *solar contribution within hybrid*
s0 = *stand-alone solar*

Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

References

[1] Turchi, C., 2010. "Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM)," NREL/TP-550-47605.

[2] Zhou, C., E. Doroodchi, and B. Moghtaderi, 2013. "An in-depth assessment of hybrid solar–geothermal power generation," *Energy Conversion and Management*, **74,** 88-101.

[3] Mathur, P.N., 1979. "An Assessment of Solar-Geothermal Hybrid System Concepts," Report ATR-79(7773-01)-2, under contract EY-76-C-03-1101, Aerospace Corporation, El Segundo, CA.

[4] Stoffel, T., D. Renné, D. Myers, S. Wilcox, M. Sengupta, R. George, and C. Turchi, 2010. "Concentrating Solar Power, Best Practices Handbook for the Collection and Use of Solar Resource Data," NREL/TP-550-47465.

[5] Greenhut, A.D., J.W. Tester, R. DiPippo, R. Field, C. Love, K. Nichols, C. Augustine, F. Batini, B. Price, G. Gigliucci, I. Fastelli, 2010. "Solar-Geothermal Hybrid Cycle Analysis for Low Enthalpy Solar and Geothermal Resources," Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29.

[6] Wendt, D.S., and G.L. Mines, 2013. "Simulation of Air-Cooled Organic Rankine Cycle Geothermal Power Plant Performance," Idaho National Laboratory, INL/EXT-13-30173.